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THE ROLE OF DYNAMIC RECRYSTALLIZATION IN PRODUCING GRAIN REFINEMENT AND GRAIN COARSENING IN MICROALLOYED STEELS

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SUMMARY

The critical strain criterion $\varepsilon_p = \varepsilon_x$ for the transition from cyclic to 'continuous' recrystallization is demonstrated to be invalid for the high temperature deformation of austenite in tension and in compression. The role of the strain and strain rate gradients present in solid torsion bars in raising the apparent torsion peak strain ε_p above the ε_p values obtained from homogeneous tension or compression testing is clarified. A similar, and larger, effect is shown to cause discrepancies in the torsion values of the recrystallization strain ε_x. An alternative criterion for the transition is derived, based on the grain size measurements performed by Sakai and co-workers on a 0.16% C steel deformed in the γ range of temperatures. Their observations indicate that *cyclic* flow curves are associated with grain *coarsening* and that *single peak* flow curves are associated with grain *refinement*. The critical condition is $D_o = 2D_s$, where D_o and D_s are the initial and stable grain sizes respectively. The relative grain size model is tested and confirmed in critical tests performed on a 0.115% V, a 0.035% Nb and a 0.040% Nb - 0.30% Mo microalloyed steel. These results indicate that single peak behaviour is caused by the 'necklace' or 'cascade' recrystallization of coarse-grained materials, which produces a large spread in the nucleation strain ε_c, and consequently a highly unsynchronized form of local recrystallization. By contrast, recrystallization is nearly completely synchronized in fine-grained materials, because the high density of grain nuclei leads to a small spread in the nucleation strain.

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FOREWORD

This report summarizes the progress of research done under CANMET/DSS Contract No. 20SU.23440-0-9179: "Prevention of Duplex Grain Structures in Controlled-Rolled HSLA Steel Plate - Phase I", during the period of June 1, 1981 to March 31, 1982, by Professor J.J. Jonas, Dept., of Mining and Metallurgical Engineering, McGill University.

The overall objective of three proposed phases of the research is to determine the causes of the undesirable duplex grain structure which develops during controlled rolling of microalloyed high strength steels, and to examine processing methods of preventing or minimizing the duplexing of the steel microstructure. The results of this research will be useful in the design of processes to achieve improved strength and toughness properties in high strength steel plate for linepipe, structural, and marine applications.

Much of the Phase I work has studied the hot deformation conditions and mechanisms which produce either grain coarsening or grain refinement during dynamic recrystallization. The results will relate to hot rolling conditions which produce dynamic recrystallization of austenite, and will also apply to understanding the effects of static recrystallization on grain structure after the austenite has been deformed in the rolling pass.

The Phase I work also included development of hot torsion tests to simulate a plate rolling schedule with roughing deformation in the full-recrystallization temperature regime, cooling without deformation to the no-recrystallization temperature regime, and finishing deformation. The tests are designed to determine how mixed grain structures can be eliminated and to establish the limiting ferrite grain size which can be produced in the transformed product.

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Ottawa, May 4, 1982

Introduction

The conditions that favour the occurrence of dynamic recrystallization during control rolling are relatively well-known (1,2). These include the following: relatively high temperatures and low strain rates, large accumulated strains (i.e. retained work hardening without static recrystallization), and a low total concentration of alloying elements (3). Although dynamic recrystallization does not always take place under industrial conditions, when it *does* occur, it produces both textures (4) and grain size distributions (5) that differ from those associated either with static recrystallization between passes, or with the *absence* of static recrystallization, i.e. under dynamic recovery or 'pancaking' conditions.

It has been reported by numerous authors (6-11) that when dynamic recrystallization is initiated, it can lead to flow curves that are either periodic (multiple peak) or 'continuous' (single peak) in nature. Less well known is the close association between *cyclic* flow curves and *grain coarsening* on the one hand, and between the flow softening that follows a *single* stress maximum and *grain refinement* on the other. The cause-and-effect relationship between the *sense* of grain size change and the *macroscopic behaviour* of the flow stress was first pointed out by Sakai and co-workers in Japan (12-15). It will be the first aim of the present paper to review briefly the work of these researchers, with particular reference to its application to the thermomechanical processing of austenite. After a presentation of the general principles enunciated by these investigators, some results will be described which were obtained recently on a series of microalloyed steels. These will be shown to support the rationalization proposed by Sakai et al. (12-15), and to confirm the key roles played by 'necklace' or 'cascade' recrystallization and size saturation during grain refinement and by boundary impingement during grain coarsening (16).

Limitations of the Critical Strain Model for Dynamic Recrystallization

The classical explanation for the transition from periodic to single peak recrystallization was proposed by Luton and Sellars in 1969 (10). On the basis of torsion testing results obtained on nickel and nickel-iron alloys, they showed that *cyclic* recrystallization occurred when the peak strain ε_p was *greater* than the recrystallization strain ε_x. (Here $\varepsilon_x = \varepsilon_s - \varepsilon_p$, where ε_s is the strain at which the flow stress first goes through its mean value at the start of the second flow stress cycle.) Conversely, *single peak* recrystallization took place when ε_p was *less* than ε_x, where in this case $\varepsilon_s = \varepsilon_p + \varepsilon_x$ is the strain at which the steady state of flow is first attained. The critical strain criterion of Luton and Sellars appears to work quite well for the *torsion* testing of steel, as illustrated in Fig. 1a. Presented here are values of ε_p and ε_x abstracted from the data of Rossard and Blain (7), which were determined at 1100°C on a 0.25% plain C steel. The intersection of the two curves at a stress value of about 46 MPa should be particularly noted.

It is of interest that the $\varepsilon_p = \varepsilon_x$ condition does not appear to apply to testing in tension or in compression, as clearly demonstrated by Sakai and co-workers (12-15). Their *tension* results are displayed in Fig. 1b for a 0.16% C steel deformed at various strain rates and at temperatures from 890 to 990°C. The absence of an intersection is evident in this plot, as well as in the curves of Fig. 1c, which represent the critical strains obtained by Petkovic et al. (11) on a 0.68% C steel which was strained in *compression*.

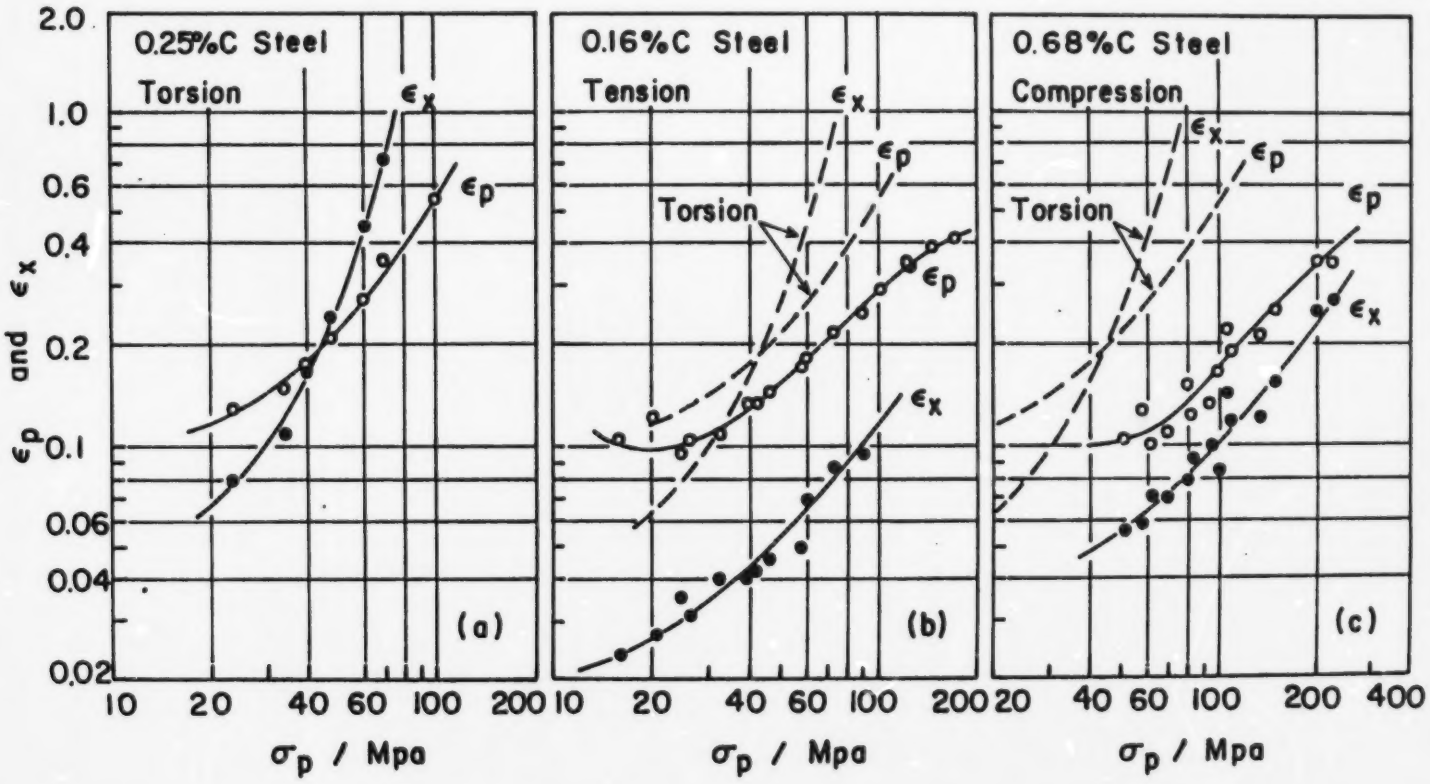

Fig. 1 Dependence of ε_p and ε_x on the peak stress σ_p. (a) Determined from the *torsion* flow curves of Rossard and Blain (7) (note intersection). (b) Determined from the *tension* data of Sakai et al. (13,14). Note that ε_p and ε_x do not intersect in this case. (c) Determined from the axisymmetric *compression* data of Petkovic et al. (11). Again the ε_p and ε_x curves do not intersect.

Primary Differences Between Torsion Testing and Deformation in Axisymmetric Tension or Compression

It is apparent from Fig. 1 that the peak strains determined in tension or compression are generally *lower* than those obtained in torsion testing. This can be attributed to the strain and strain rate gradients present in *solid* torsion samples. As a result of this gradient, the peak strain is attained first in the outermost layer of a cylindrical sample, the condition being satisfied later and later (in time) in shells of material of successively smaller radius. Because of this effect, and of the way in which the individual shells contribute to the macroscopic torque, the maximum in the couple is observed *later in time* than the moment associated with the peak stress in the outermost shell. For this reason, the stress/strain curves deduced from torque/twist data generally display maxima at strains *greater than* the peak strains determined in tension or compression at the same temperature and effective strain rate (13,14). Although this disparity is not likely to affect the results obtained from the torsion testing of *tubes*, it does apply to the differences between torsion testing and other homogeneous modes of deformation such as rolling or plane strain tension or compression (16).

There is a further component of difference between torsion-based flow curves and those determined in axisymmetric tension or compression which applies to the results of *both* tube and solid bar experiments. This is associated with the differences in the *textures* developed in these three modes of testing, as well as in the rates of *work hardening*. These two effects combine to further increase the differences between the peak strains deduced from torque/twist data and from axisymmetric testing (17, 18). By contrast, because torsion and rolling are both modes of plane strain deformation, the work hardening and texture differences between these two methods of straining are considerably smaller than between say torsion and either extrusion or continuous forging, both of which are axisymmetric in nature (17,18).

A similar but more complex consideration affects the apparent recrystallization strain ε_x determined from the torsion testing of solid bars (16). As is evident from Fig. 1, the differences between the torsion-based and axisymmetric values of ε_x are *even greater* than between the torsion-based and axisymmetric values of ε_p. This is because ε_x is obtained experimentally from the relation $\varepsilon_x = \varepsilon_s - \varepsilon_p$, and thus includes components of 'time averaging' from *both* ε_s and ε_p. This effect is discussed in greater detail in Reference 16.

The Evolution of Grain Size with Strain During the Dynamic Recrystallization of Austenite

An alternative to the critical strain condition as an explanation for the transition in recrystallization behaviour was proposed by Sakai and co-workers in 1976 (12). Their interpretation was based on results they obtained in tension on sheet specimens of a 0.16% C plain carbon steel. Their samples were deformed in vacuo in specially constructed tensile machines which were fitted with a H_2 gas quenching attachment. This facility permitted cooling rates of 2500°C/s to be attained and thus enabled the austenite grain structures present at each selected strain to be preserved for study at room temperature. Their results are summarized in Fig. 2, from which it is apparent that there were two distinct classes of behaviour.

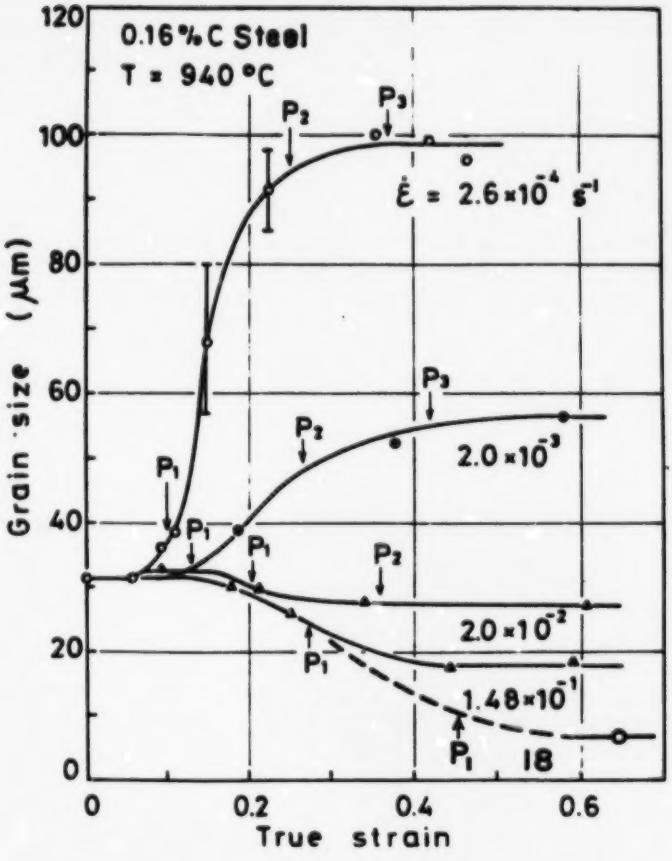

Fig. 2.
Effect of strain and strain rate on the mean grain size of a 0.16% C steel deformed in tension at 940°C. P_i identifies the strain at the ith flow stress peak. Note that *multiple peaks* are observed during grain *coarsening* (and when grain refinement produces less than a 2:1 reduction in grain size). Conversely, a *single peak* is observed when the grain *refinement* ratio is more than 2:1 (12,14).

When the testing strain rate was *low* (e.g. 2.6×10^{-4} or 2.0×10^{-3} s^{-1}), *grain coarsening* was observed. The coarsening was associated with the occurrence of *multiple stress peaks*; the peak strains are identified as P_1, P_2 and P_3 in Fig. 2. When the testing strain rate was relatively *high* (e.g. 1.48×10^{-1} or 18 s^{-1}), *grain refinement* took place. Under these conditions, which are closer to industrial rates of straining, only a *single stress peak* was apparent. The transition from multiple to single peak behaviour did *not* occur, as perhaps might be expected, at $D_o = D_s$, where D_o and D_s are the initial and stable grain sizes respectively. Thus the transition in the nature of the flow curve did not coincide with the transition from grain coarsening to grain refinement. Instead, multiple peaks appeared to persist as long as the grain refinement ratio did not exceed $D_o/D_s = 2$.

Thus the critical factor appears to be whether or not 'cascade' or 'necklace' recrystallization can take place (16). Under the latter conditions, a different critical strain ε_c is associated with each strand of the necklace, leading to a large spread in the nucleation strains pertaining to the different layers of material involved in the first full cycle of recrystallization. By contrast, when $D_o/D_s < 2$, cascade growth is not possible, and the initial structure is completely replaced in a single concurrent cycle of recrystallization. In this case, the spread in the nucleation strain is of course much smaller (16). The observations of Sakai and co-workers suggest that there is a link between the spread in

the nucleation strain ε_c and the relative grain size $D_o/2D_s$. This is a point to which we will return after a consideration of further experimental evidence regarding the characteristics of grain coarsening and grain refinement during deformation.

A Grain-Size-Based Critical Condition for Cyclic Recrystallization

The two kinds of behaviour described above can be distinguished in terms of the microstructural mechanism map of Fig. 3. Here the testing conditions are represented by the vertical coordinate of temperature-corrected strain rate Z or by its equivalent, the peak stress σ_p, or the

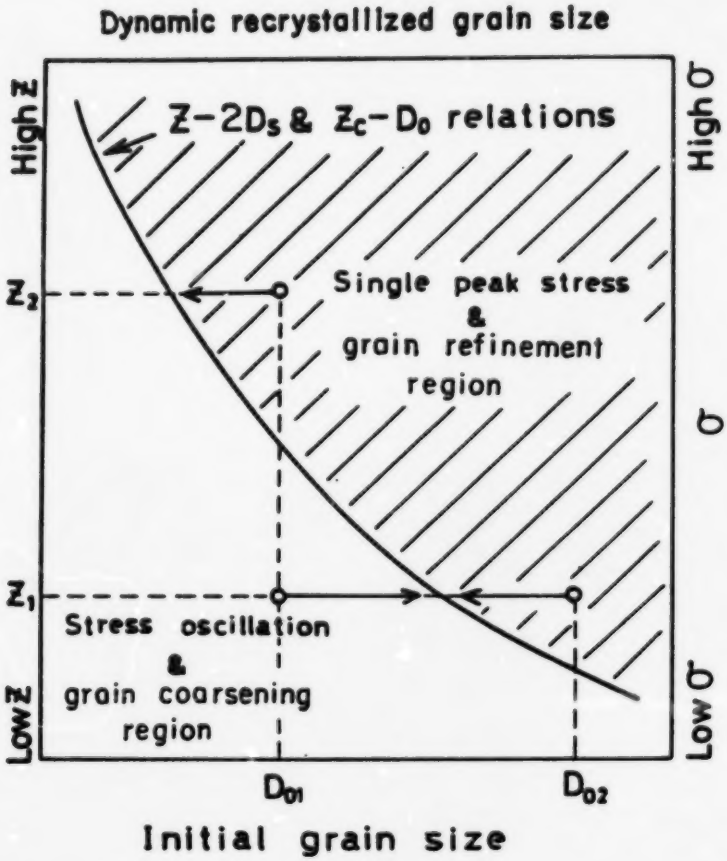

Fig. 3. The curve describing the Z-$2D_s$ and Z_c-D_o relations distinguishes the single peak from the multiple peak region. When testing is carried out at a fixed temperature and strain rate (fixed Z), grain coarsening and repeated stress oscillations occur as long as each successive $D_o < 2D_s$ (e.g. at D_{o1} and Z_1). Conversely, when $D_o > 2D_s$, there is grain refinement and a single stress peak (e.g. at D_{o2} and Z_1). When a fixed initial grain size is used (e.g. D_{o1}), stress oscillations and grain coarsening are associated with $Z < Z_c$ (e.g. $Z_1 < Z_c$), and a single stress peak and grain refinement with $Z > Z_c$ (e.g. $Z_2 > Z_c$).

steady state stress σ_s. Two alternative horizontal axes are shown, the initial grain size D_o and the equilibrium grain size D_s, both of which enter into an interpretation of the diagram. The full line dividing the cross-hatched from the plain region describes the *dependence* of $2D_s$ on Z (and therefore the *correlation* between $2D_s$ and σ_p) that is observed. The same curve also specifies the *dependence* of Z_c on D_o, where Z_c is the critical value of Z at which, for a fixed value of D_o, the nature of the flow curve changes from cyclic to single peak, or vice versa.

It is of interest that two distinct types of experiment are represented in this diagram. A 'vertical' series of tests corresponds to the classical case where a *fixed* initial grain size is taken, e.g. D_{o1}, and where Z is varied (by changing the temperature or the strain rate) from say Z_1 in the grain coarsening region to Z_2 in the grain refinement region. As Z is increased, so do the oscillations in the flow curves gradually disappear, as has been demonstrated by numerous researchers (5-16). The second type of experiment corresponds to a 'horizontal' series of tests, in which the temperature-corrected strain rate is held constant at Z_1 and the *initial* grain size is varied over the range D_{o1} to D_{o2}. In order to test the validity of Fig. 3, such a series of 'horizontal' tests was carried out, the results of which will now be described.

A Critical Test of the Grain-Size-Based Criterion Performed on a Vanadium Microalloyed Steel

The microalloyed steel selected for the critical experiment contained 0.06% C, 1.2% Mn, 0.115% V and 0.006% N. In order to produce a range of initial grain sizes, individual samples were austenitized at temperatures of 975, 1000, 1030, 1100 and 1260°C. This led to grain sizes in the range 65 to 300 μm, as indicated in Fig. 4. The samples were hot compressed in a modified Instron testing machine (5) at a constant true strain rate of 1.4×10^{-3} s^{-1} and at 975°C. For this Z condition, D_s can be estimated to be about 50 μm, so that $2D_s$ = 100 μm. It is apparent from Fig. 4 that when D_o was less than $2D_s$, i.e. for the 65 and 80 μm material, multiple stress peaks were induced, which were not damped out in the 65 μm material by the time the experimental strain limit of 1.0 was reached. It should be noted, however, that the amplitude of the oscillations decreased with strain. In terms of Fig. 2, this means that the amplitude decreases as each successive wave of grain coarsening brings the mean grain size closer to D_s.

For the coarse-grained materials, i.e. when D_o was greater than $2D_s$, a single marked flow stress peak was observed, followed by a small, but distinct, second peak. According to the results obtained on plain carbon steels (12-16), this is accompanied by the occurrence of grain refinement, which comes to an end when the stable mean grain size D_s is attained. This type of behaviour corresponds to industrial rolling after either continuous casting, or after reheating to a fairly high temperature.

Effect of Microalloying on Grain Refinement and Grain Coarsening

The usual effect of the presence of microalloy elements on the shape of the flow curve is depicted in Fig. 5. Here it can be seen that, as the overall 'strength' of the alloying additions is increased, the oscillations evident in the case of the plain carbon material gradually disappear. The tests in Fig. 5a, which were conducted at 1075°C, were all completed in about 20 s; thus no precipitation of nitrides or carbonitrides occurred

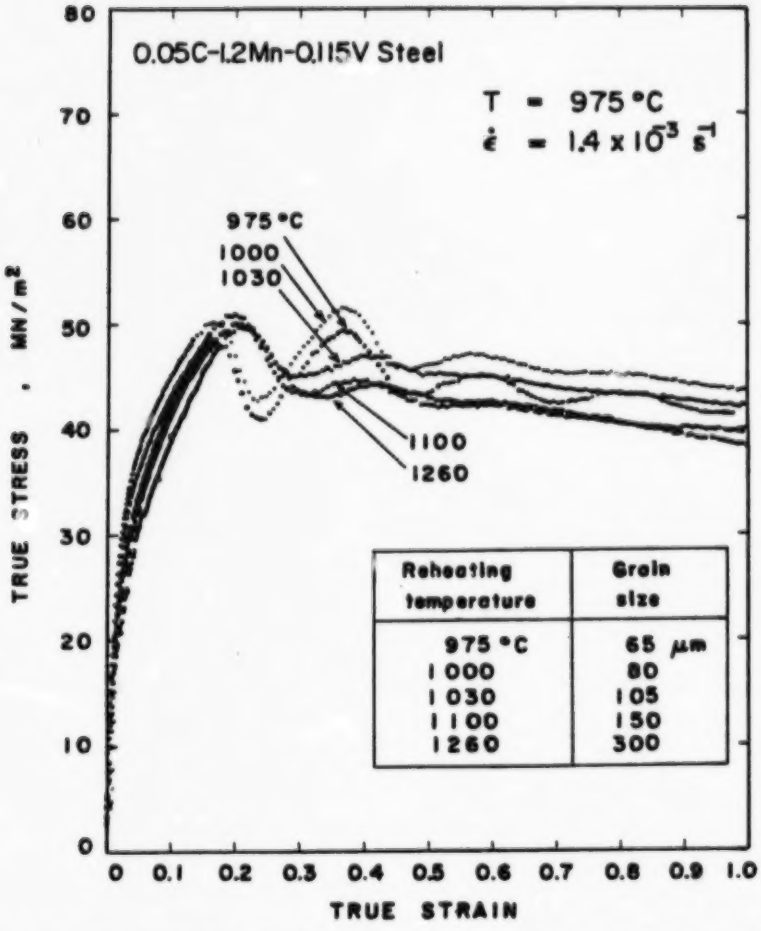

Fig. 4 Critical experiment designed to test the model of Fig. 3. A 0.05% C - 1.2% Mn - 0.115% V steel was austenitized at a series of temperatures ranging from 975 to 1260°C selected to produce initial austenite grain sizes of 65 to 300 μm, respectively (see inset). Testing was carried out in axisymmetric compression at 975°C and 1.4×10^{-3} s^{-1}, for which $2D_s \approx 100$ μm. Cyclic σ/ε behaviour was observed when $D_o < 2D_s$; by contrast, single peak behaviour was obtained when $D_o > 2D_s$.

during the experiments (19,20). The differences between the curves are therefore attributable entirely to the influence of the alloying elements *in solution*.

In this case, however, the rationalization based on the present model differs somewhat from the one proposed above for Fig. 4. In that experiment, although the *final* grain size was the same for all five tests, the *initial* ones were not, leading to relative grain sizes $D_o/2D_s$ both larger and smaller than one. By contrast, in the present instance, it was the *initial* grain size which was held constant. The change in the $D_o/2D_s$ criterion was produced instead by varying the *stable* grain size D_s (at each fixed temperature and strain rate) through the influence of the microalloying elements in solution on the recrystallization process. For example,

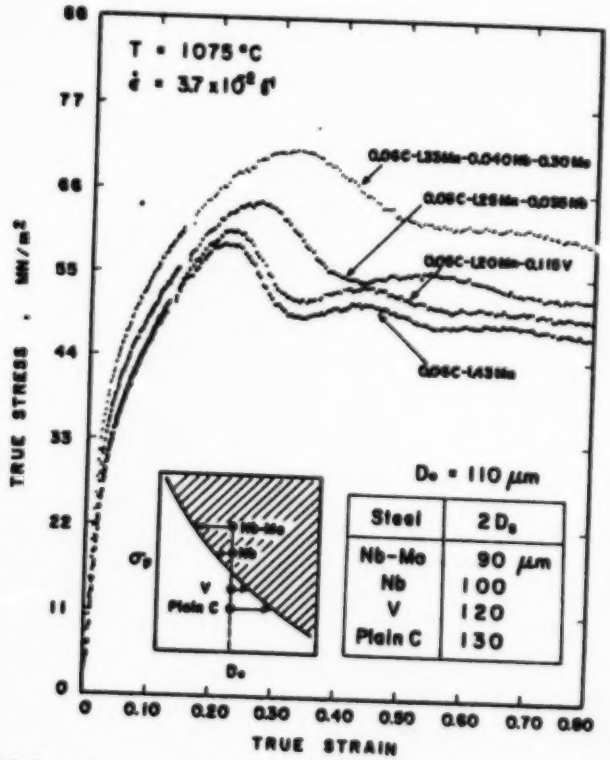

Fig. 5(a). Effect of microalloy addition on the shape of the flow curve. The plain carbon and 0.115% V steels undergo cyclic recrystallization because $D_o/2D_s < 1$. The Nb and Nb-Mo grades display single peak behaviour because $D_o/2D_s > 1$. The transition in the character of the curves can be ascribed to the effect of the solute elements on the stable grain size produced at a given temperature and strain rate.

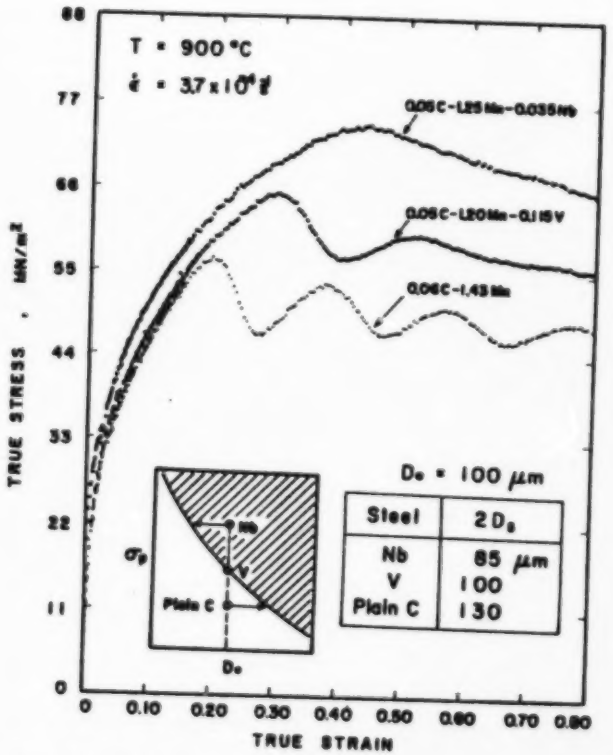

Fig. 5(b). Effect of dynamic precipitation on the shape of the flow curve. The plain carbon steel exhibits cyclic recrystallization because $D_o/2D_s$ = 0.77. Conversely, the Nb steel, with $D_o/2D_s$ = 1.18, displays single peak behaviour. The V steel, with $D_o/2D \approx 1$, is at the transition between the two types of flow. The greater difference between the three steels apparent above than in Fig. 5(a) is attributable to the occurrence of dynamic precipitation during the compression of the two HSLA materials.

D_s for the C and V steels is about 65 and 60 μm, respectively, so that the relative grain size $D_o/2D_s$ is 0.85 and 0.91, which is consistent with the occurrence of grain coarsening and stress oscillations. For the Nb and Nb-Mo steels, on the other hand, D_s is about 50 and 45 μm, respectively, so that $D_o/2D_s$ is 1.10 and 1.22. As these values are greater than one, grain refinement and single peak behaviour are indicated.

A similar explanation applies to the curves of Fig. 5b. Here the initial grain size is again constant and the addition of alloying elements changes the character of the flow curves by reducing D_s. However, because these experiments were carried out at 900°C, and each test took about 2000 s to complete, the precipitation of Nb(CN) and of VN took place in the 0.035% Nb and 0.115% V steels, respectively (19,20). Thus the retardation of recrystallization by the solute effect was supplemented by a component of precipitate retardation. It is in fact the occurrence of carbonitride precipitation that is responsible for the considerable increase in the peak stress and strain in the HSLA steels over those associated with the plain carbon grade. This is why there is a larger difference in Fig. 5b between the carbon steel behaviour on the one hand and the vanadium and niobium steels on the other than in Fig. 5a, where no precipitation is taking place.

How to Make a Microalloyed Austenite Undergo Cyclic Recrystallization

Although the addition of elements with appreciable solute and precipitate effects generally promotes the transition from cyclic to single peak flow (cf. Fig. 5), this trend can be successfully reversed by making use of the principles described above. In Fig. 6, for example, *it is the Nb-Mo steel which exhibits oscillations and the plain carbon material which displays a single peak.* This somewhat paradoxical result was produced by ensuring that $D_o/2D_s$ for the plain carbon sample was *greater* than one (375/270 = 1.39), and that, conversely, $D_o/2D_s$ for the Nb-Mo alloy was *less* than one (150/270 = 0.55). Such a role reversal between the two types of steel helps to confirm the critical importance of the relation between the original and equilibrium grain sizes which has been the principal subject of the present paper.

The Link Between the Relative Grain Size $D_o/2D_s$ and the Spread $\Delta\varepsilon_c$ in the Nucleation Strain

The conclusion that the transition between single and multiple peak behaviour occurs at the critical condition $D_o = 2D_s$ is well supported by the observations reported by other workers (21-24). A detailed analysis of such results is given in Reference 16. We turn instead to a consideration of how it is possible for the *character* of the flow curve to change as sharply as it does in Fig. 4 when the temperature and strain rate are both held constant, and *only the initial grain size is changed.* Similar questions can be framed regarding the nature of the flow curves in Fig. 5. These were also determined at constant temperature and strain rate, but the alloy concentrations associated with the various curves are different at the *same* initial grain size.

Some light can be shed on these matters by considering the relative densities of dynamic recrystallization nuclei under the above experimental conditions. For simplicity, in what follows, the possibility of nucleating new grains at deformation bands or inclusions is neglected and all new

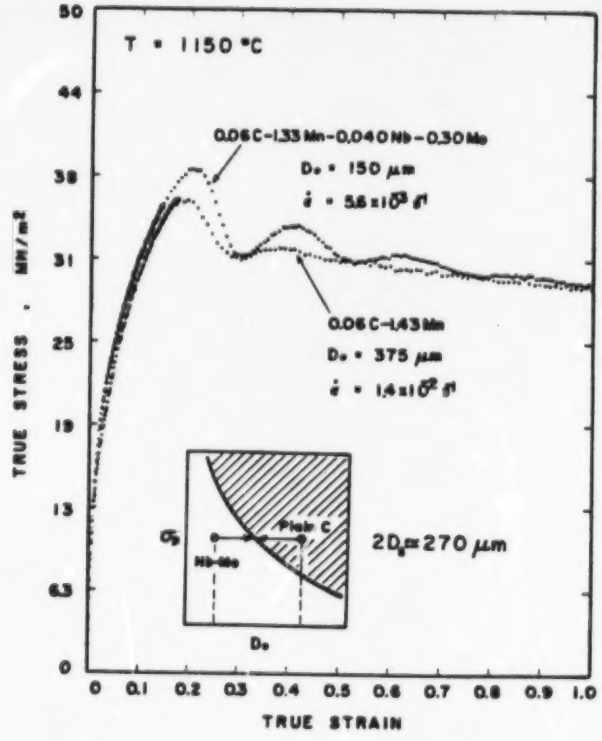

Fig. 6.
A further critical experiment designed to test the relative grain size model. Here the Nb-Mo steel exhibits *cyclic* behaviour and the plain carbon material undergoes a *single cycle* of flow softening. Although the stable grain sizes are similar for the two materials, the use of two different reheating temperatures (1260 and 1150°C for the plain carbon and Nb-Mo grades, respectively) led to relative grain sizes larger and smaller than one, and therefore to the observed inversion of the normal relationship between the two types of behaviour (Fig. 5a).

grains are assumed to form solely at the existing grain boundaries. Under these conditions, we can define $N_s = 3P/D_s$ as the equilibrium density of nuclei present during steady state flow, where P is the probability per unit surface area of a grain boundary site being activated. Thus the critical density associated with the criterion $D_o = 2D_s$ is $N_o^* = 3P/2D_s$. When N_o ($= 3P/D_o$) > N_o^* (i.e. in fine-grained materials), the flow is periodic; conversely, when $N_o < N_o^*$ (i.e. in coarse-grained materials), only one cycle of flow softening is observed.

A possible explanation of this behaviour can be based on the link between the nucleation strain ε_c (and particularly the *spread* in the nucleation strain $\Delta\varepsilon_c$) and the relative nucleus density N_o/N_o^*. When N_o/N_o^* is high, there are *many* potential nucleation sites within every future stable grain. Thus nucleation can be expected to have occurred in *all* regions within a short interval after the critical strain ε_c is attained in the most favourably oriented region. The *spread* in the critical strain $\Delta\varepsilon_c$ between the most and least favoured regions is likely to be small in this case. This is equivalent to the condition (16):

$$\Delta\varepsilon_c < \varepsilon_c \qquad (1)$$

It signifies that the entire material is essentially at the same stage of the recrystallization process at a given moment. It is implicit in this view that several recrystallization cycles are needed to attain D_s because the initial nucleus density N_o is too high, so that too fine an intermediate grain size D_s' is produced in the first cycle. According to this model, the number of recrystallization cycles depends on the disparity between N_o and N_o^*.

By contrast, in the coarse-grained material, $N_o < N_o^*$, and there is a *scarcity* of potential nucleation sites within every future stable grain. Indeed, there are NO potential nucleation sites in the regions corresponding to the inner strands of 'necklace' recrystallization until *after* the immediately preceding strand has been produced. Thus $\Delta\varepsilon_c$ generally exceeds ε_c under these conditions; i.e.

$$\Delta\varepsilon_c > \varepsilon_c \qquad (2)$$

signifying that the different volume fractions of the material are at entirely different stages of the recrystallization process. According to this model, flow softening continues until the innermost regions of coarse-grained materials have participated in the recrystallization process. Because of the relative scarcity of nucleation sites, if D_s is not attained in one complete cycle of recrystallization, a faint second cycle is observed.

It is evident from the above that, in fine-grained materials, i.e. when $N_o > N_o^*$ and $D_o < 2D_s$, the progress of recrystallization is highly *synchronized* and the macroscopic flow curve readily reflects the *local* cycles of work hardening and recrystallization. Conversely, in coarse-grained materials, i.e. when $N_o < N_o^*$ and $D_o > 2D_s$, the progress of recrystallization is highly *unsynchronized* and only an *average* flow stress can be measured, which obscures the local cycles of strain hardening and restoration.

Conclusions

1. The critical strain model for explaining the transition from periodic to single peak flow in high temperature austenite does not apply to tension or compression, or to other homogeneous modes of deformation such as rolling and upset or continuous forging. This is because of the strain and strain rate gradients present during the torsion testing of solid bars, the type of test that provided the data on which the model was based. As a result of the gradient, the peak strain ε_p is attained progressively later as the radius of an elemental shell in the solid bar is decreased. In this way, the peak torque (and therefore the peak stress determined experimentally) is attained *later* (and at a larger effective strain) than in the outermost layer of the bar, or than in a tensile test performed at the effective strain rate associated with the outermost layer. This effect is compounded for the recrystallization strain ε_x, so that the differences between the values of ε_x determined in torsion and compression are even greater than the differences in the torsion and compression values of ε_p.

2. In a 0.16% C plain carbon steel tested in the γ range, periodic flow curves are associated with grain coarsening. By contrast, single peak flow curves are observed when the grain refinement ratio is at least 2:1. The criterion that distinguishes between the two types of behaviour is $D_o = 2D_s$, where D_o and D_s are the initial and equilibrium grain sizes, respectively. Under industrial conditions of austenite processing, because of the coarse grain size produced on reheating and the lower subsequent processing temperatures, single peak behaviour is generally expected, accompanied by grain refinement.

3. The critical grain size model was verified in a 0.115% V, a 0.035% Nb and a 0.040% Nb - 0.30% Mo microalloyed steel, under both 'solute retardation' conditions, as well as when there is an additional component

of 'precipitate retardation'. It is evident from these results that 'necklace' or 'cascade' recrystallization (in which grain growth is halted by concurrent deformation) is associated with single peak behaviour. Conversely, when grain growth is terminated by boundary impingement instead, as under grain coarsening conditions, the flow curve is cyclic.

4. An analysis of these two types of behaviour indicates that the necklace nucleation that takes place in coarse-grained materials leads to a large spread in the nucleation strain and therefore to a form of dynamic recrystallization which is highly unsynchronized. In fine-grained materials, on the other hand, there is a high density of nuclei present, as a result of which the spread in nucleation strain is small and all regions of the material are at approximately the same stage of the recrystallization process.

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